REMARKS

#1. Various amendments have been made to the specification to reflect the restriction of the claimed invention to that of a laser cavity only, rather than the broader optical resonator of the original claims. Accordingly, some parts of the disclosure have been deleted.

Also, applicant has made amendments to the description to eliminate the use of several terms in reference to the same structural element. In particular, the more narrowly claimed laser cavity of the newly amended claims is reflected in the amendments to the remaining specification. Such terms as "optical resonator", "optically resonant structure", and "resonator" were originally used in addition to the usage of "laser cavity" to reflect the more broad usage of the disclosed structure as an optical resonator. In the amended specification, the disclosed structure is referred to as a laser cavity structure only, so that there is a clear relationship to the more narrowly claimed invention of the amended claims.

Also, applicant has amended the specification so that the "gain medium" may be clearly distinguished from "process media", by making the former singular and the latter plural.

Applicant has also amended the specification to include reference to the Emmett patent cited in the Action.

Applicant has also amended the specification with the insertion of qualifiers such as "effective", "normally", and "substantially" to avoid overly restrictive interpretation.

Also, applicant has amended the specification so that the original claimed matter in the specification of record is identically found in the description. Accordingly, the phrase of the original claims concerning the possibility that a "gain medium provides a narrow fluorescence spectrum" has been inserted in the description. Also, the phrase of the original

claim concerning the possibility that "the gain medium is pumped by a discharge" has also been inserted in the description.

Also, since the invention maybe found to be relevant to several fields with slightly different use of terminology, terms such as "finesse" and "low order modes" have been specifically defined in a manner consistent with their common usage within the fields of the invention.

Also, the applicant has deleted text in the description that refers to microspheres, since, though the suggested microsphere structure may eventually be fabricated to advantage, the suggested microsphere is not a preferred embodiment and does not provide the advantages of the preferred embodiments.

Because of the number of amendments made to the specification of record, applicant has filed marked-up and clean copies of the specification in this response, under C.F.R. § 1.125, in case such action is required by the office.

Applicant hereby declares that no new matter has been added to the amended specification of the present response.

#2. The Action contains nine (9) separate paragraphs that comprise the claim rejections, followed by a Prior Art section and examiner's contact information.

The first paragraph of the Office Action comprises claim rejections of claims 3 and 5 under 35 U.S.C.§ 112. Applicant acknowledges the failure of claims 3 and 5 to specifically point out and distinctly claim the subject matter. Applicant has deleted claims 3 and 5, and has submitted replacement claims, claims 35 and 36, in the present response to overcome this rejection.

The second paragraph of the Office Action comprises claim rejections of Claims 1, 3-5, 8-11, 13, 17, 18, 19, and 21 under 35 U.S.C.§ 103. The following third through ninth paragraphs of the Action comprise an explanation of the rejections under 35 U.S.C.§ 103.

The third paragraph of the Office Action comprises a detailed explanation of the claim rejections of the second paragraph. All claims of record have been rewritten and replaced with new claims 22 to 45 in order to define the invention more particularly over the cited references. These new claims are all submitted to be patentable over the cited references. Arguments for supporting patentability of the new claims, and overcoming rejections under U.S.C. § 103, follow this section.

The fourth paragraph of the Office Action comprises a single sentence citing the specification, by Emmett, of a thin film structure possessing 100 to 100,000 layers, which Office suggests could be adapted for other purposes. Applicant submits that the film structure elements common to both Emmett and the present invention are predicted by the well-known mathematical formulation presented in the description; however, Applicant argues that such common elements do not anticipate the novel physical features or principles of laser operation disclosed in the present invention.

The fifth paragraph of the Office Action points out that claims 8-11 are intended use claims, which do not satisfy the requirements of an apparatus claim. Applicant has deleted claims 8-11 in the amendment, and has introduced new claims, claims 31-35, which are submitted as now properly claiming the intended additional structural means.

The sixth paragraph of the Office Action cites column 4 lines 46-49 of Baer, in regards to claim 13, wherein Baer cites use of a solid state medium. Applicant has deleted claim 13, and has introduced a new claim, claim 25, which is respectfully submitted as allowable as being dependent on new independent claim 22, which is argued as allowable.

The seventh paragraph of the Office Action points out that lasers are well known for providing, by various techniques, narrow-band emission. Applicant has deleted claim 16 and has added a new dependent claim, claim 16, to more clearly specify that the fluorescence spectrum of the gain medium is the intrinsic fluorescence spectrum (resulting from spontaneous emission) of the gain medium, rather than the spectral output resulting from operation of the claimed cavity as a laser. Applicant also submits that the term "fluorescence spectrum" is unambiguously known in the art to be the spontaneous (not stimulated) spectral emissions of a particular medium.

The eighth paragraph of the Office Action comprises a rejection of claims 6, 7, 14, and 15 under 35 U.S.C.§ 103. Applicant has deleted these claims and has added new claims in this amendment, claims 29,30, and 38, which Applicant believes to be allowable as dependent on new independent claim 22, which is also held to be allowable.

The ninth paragraph of the Office Action comprises a rejection of claims 2, 12, and 20 under 35 U.S.C.§ 103. Applicant has deleted these claims and has added new claims in this amendment, claims 23 and 24, which Applicant believes to be allowable as dependent on new independent claim 2, which is also held to be allowable.

The tenth paragraph of the Office Action cites US patent 4,651,034, as a possible relied-upon reference in a future office action. It is assumed in the present response that there was a typo in citing this patent number, and that the actual number intended was US patent 4,615,034, which was included with the Action. Applicant addresses this possible reference in the following arguments for allowability.

Arguments by Applicant for Allowability of New Claims Under 35 U.S.C. § 103

#3. All structural means for mode selection that are taught in the relied-upon combination of Baer and Emmett are contrary to the structural means for mode selection of the present invention.

It is pointed out in the Action that Baer specifies preferred modes. However, applicant respectfully submits that, while preferred modes may be produced in the Baer invention, preferred modes are produced by any lasing cavity that possesses higher containment (higher cavity Q) or pumping rates for some portion of its cavity modes. Thus, this characteristic applies to almost all lasers and is therefore not a meaningful distinction for anticipating the present invention without addressing the physical and structural means of mode selection being claimed.

The multilayer coating of Emmett is disclosed only as a damage resistant narrow-band reflector for handling the high energy densities present in broadband light sources, such as flashlamps. Emmett does not describe utilizing the angle-dependent properties of the disclosed coating structure of the present invention, much less the use of such angle-dependence for enabling a mode-selection means in a laser cavity.

In Baer, preferred modes are selected by selecting the angle of incidence with which a pumping laser beam is directed onto the surface of the disclosed microsphere. Applicant finds no indication that Baer intended some other means of mode selection other than the described structural means of utilizing pumping angle. Baer thus teaches a path and structural means that is mutually exclusive to the structural means taught in the present invention, since mode selection cannot be provided by the Baer means of selecting a pumping angle if the mode selection is already predetermined by the coating structure of the present invention.

It may further be observed that there is no suggestion, description, or implication, in the relied-upon references of Baer and Emmett, that any coating structure, much less structural elements of Emmett, might be used as means for limiting the number of modes (and more particularly, of a selected wavelength) in a resonant cavity.

#4. The described structural means for coupling radiation from the Baer cavity are contrary to the claimed structural means of coupling radiation from the cavity of the present invention.

The structural coupling means of Baer are those consistent with a high-index cavity that supports TIR. The structural coupling means of the present application, specified as either a central coupling structure or a discontinuity in the reflective coating, are distinct from those of Baer because the opposite type of cavity, a low-index cavity, is being utilized.

A useful laser must include means for extracting energy from the cavity. However, it may be noted that the coupling of optical energy out of the cavity of Baer is only described as possible by coupling of the evanescent wave into a prism or fiber, or by using the spherical cavity as a point source of 360° divergent light. The evanescent wave coupling of Baer is contrary to the structural coupling means of the present invention because the present invention utilizes a low-index cavity that does not support the total internal reflection (TIR) or the associated evanescent coupling of frustrated TIR. Operation of the spherical cavity as a point source of 360° divergent light, in Baer, is also contrary to the structural coupling means of the present invention, so that all cited operational modes of Baer are contrary to the operation of the present invention.

#5. The described and claimed invention of Baer specifies the forming of a resonant cavity *within* the gain medium, whereas the specified resonant cavity structure of the present invention is formed *outside* the gain medium.

That the intended modes of Baer are only the modes of the microsphere volume itself, rather than those of a specific coating structure, is further confirmed by the claimed invention of Baer, which comprises only a resonating cavity formed within the gain medium. The claimed matter of Baer therefore excludes such a cavity disclosed in the present invention, wherein the many-layered cladding/coating of the circular cavity is itself the resonant structure that defines and delineates the disclosed resonant cavity, as well as determines the resonant mode structure existing within the gain medium.

#6. The coating of Baer is specified as an isotropic coating; whereas, the coating of either Emmett or the present invention are highly anisotropic structures.

In regards to the coating of Emmett, the applicant respectfully submits that, contrary to the Action, **there is no disclosure in Emmett of an isotropic coating.** This omission is not incidental, because the coating of Emmett is, in fact, highly anisotropic.

To establish the accepted meaning of "isotropic" and "anisotropic", the applicant has attached copied pages from the scientific dictionaries published by Oxford University Press, Cambridge University Press, and McGraw Hill. These copied pages are labeled "Appendix A." In Appendix A, the definitions of "isotropic" and "anisotropic" are clearly and consistently set forth. From these definitions, it may be established that "isotropic" refers to a physical property that is not dependent upon the direction in which it is measured, whereas "anisotropic" refers to a physical property that is dependent on the direction in which it is measured.

Although the individual material layers of the Emmett coating can be, individually, optically isotropic – as is suggested in regards to the multilayer coating of the present invention – the resulting optical structure is, by physical necessity, highly anisotropic, though this property is not utilized in Emmett. As is set forth in conjunction with FIGS. 2-5 of the present invention, the laser cavity of the present invention relies upon such highly anisotropic properties for its novel results. However, there is no suggestion in Baer that the coating structure of the present invention, or any coating structure that provides the necessary anisotropic properties, might be used.

#7. There is no suggestion or implication in the relied-upon combination of Emmett and Baer, that the relevant anisotropic features of the Emmett coating might be utilized in a laser cavity construction, or any of the novel results or applications claimed in the present invention. Also, such anisotropic properties that are required for operation of the present invention are not described or utilized in the inventive matter of Emmett.

#8. There is no suggestion, description, or implication, in the relied-upon combination of Baer and Emmett, or any other cited reference, that the features of the claimed coating structure and claimed substrate structure of the present invention might be combined, much less that such combined features might be used to provide laser operation. The present invention discloses a new principle of operation for laser cavities, for which both the specified coating structure and the cavity structure in which it is implemented are essential elements; yet, there is no suggestion, in any of the combined references, that the coated cavity structure of the present invention might be constructed, much less that the resultant structure could be used to provide laser operation.

#9. The results of an approximately linear intensity distribution, as disclosed in Baer, are contrary to the operation of the presently disclosed laser cavity.

Note that FIG. 4 of Baer describes no more than a linear – and infact, less than linear – increase in optical intensity as inversely related to the distance, R, from the spherical cavity center. The two linear intensity distributions of Baer, FIG. 4, for the coated and uncoated embodiments of Baer, are both consistent only with the intensity distribution of the obliquely reflecting whispering modes described in Baer. These described intensity distributions of Baer are contrary to the operational characteristics of the present invention. Even in its least coherent operation, the cavity of the present invention would provide not a linear increase, but, roughly, at the very least a $1/R^2$ to $1/R^3$ dependence, depending, in part, on whether the cavity is cylindrical or spherical. In the case, as in Baer, that spatially and temporally stable spherical cavity modes are established in the present invention, the intensity distribution would then be of the order of $1/R^6$. This $1/R^6$ dependence may be easily recognized, since, at the near-normal incidence reflection of the present invention, the light amplitude will sum geometrically with the $1/R^3$ dependence of the spherical cavity, and intensity (or irradiance) is defined as the square of this amplitude.

#10. In view of these differences, it is respectfully submitted that the cited combination of Baer and Emmett does not anticipate the invention as now claimed in the newly submitted claims, claims 22-45, which are held to particularly point out both a laser cavity structure and subsequent operational principles that are not anticipated by the cited art. Accordingly, applicant respectfully requests reconsideration and allowance of the present application with the above new claims.

Additional Reasons Militate In Favor Of Unobviousness

#11. Inoperative combination: The construction of a cavity structure comprising the Baer sphere in its coated embodiments, coated with the Emmett coating, does not provide any useful means of coupling energy from the cavity. The evanescent coupling described in Baer would be rendered impossible, since, in the Emmett coating, modes of the preferred wavelength are extremely, if not entirely, attenuated before reaching the outer layers of the reflective Emmett coating, regardless of whether the high-index cavity of Baer is assumed. Also, any of the solid sphere cavities of the Baer reference will support TIR, and whispering modes, when operated in the open environment described. The very high cavity Q for the resultant whispering modes in these same solid spheres make it impossible to avoid these whispering modes, which will dominate cavity operation, without modifications and features that are unsuggested in the cited references.

#12. There Are Presently No Means For Combining Emmett and Baer: There are presently no means reported for forming the required multilayer coating onto the described microsphere of Baer. Even recently improved state-of-the-art techniques for coating such small spheres have only achieved optical quality coatings for simple anti-reflection coatings, which require far less layers (3-7) with far less accuracy (corresponding to a broad-band filter for lowering reflectance a couple percent).

#13. New principle of Operation: Applicant respectfully submits that the present application discloses a laser cavity that is fundamentally different, both in its operation and in its described result, from the cavity operation described in any of the cited references, or, for that matter, the entire prior art. This may be witnessed in the operational characteristic of the applied-for cavity, wherein the ability to avoid parasitic lasing modes within the disclosed cavity effectively avoids the constraints incurred by the well-known and accepted stability diagram for laser cavities, which may be found in any standard laser text. In one aspect, the

novel operation of the applied-for cavity allows for the discrimination of "walk-off" modes of an unstable resonator to only those walking – or stationary – modes that are confined by the circular cavity. In this operational mode, a previously unstable (and high loss) cavity geometry may be rendered effectively stable (and low loss), since the cavity cannot support most of its normally associated high-loss modes, so that the loss mechanism normally associated with the same cavity geometry of the prior art is effectively eliminated. Applicant has not witnessed this principle of operation anywhere in the prior art, or in any of the relied-upon references. **Therefore, the whole is greater than the sum of its parts; the results of the present invention are not those of either reference.**

#14. Solved Different Problems: The prior art cited does not address the problems addressed in the present invention; namely, the need to uniformly irradiate a photoabsorbing medium, such as gases, vapors, or other mediums (such as an optical fiber or optical fiber preform), as is addressed in the present invention.

#15. Lack of Implementation in a Crowded Art: It should be noted that the human capacity to construct the laser cavity of the invention has existed for over three decades. Obtaining the advantages of this invention has been the object of intense and continual efforts in this same time frame. The very crowded art in this area of research attests to this effort. Therefore, if the applied-for laser structure were obvious, it would already exist in the prior art.

#16. The applicant respectfully submits that the disclosure of von Gunten, as a possible relied-upon reference, does not overcome any of the above arguments for allowability of the new claims submitted in the present amendment.

#17. Applicant wishes to thank the Supervisory Patent Examiner for his helpful assistance in the informal telephone interviews conducted prior to this response. The applicant can be reached at 520-977-6423, and would appreciate any opportunity in the future to discuss any remaining issues concerning the application.

Very respectfully,

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(date) 4/17/03

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Date

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APPLICATION FOR PATENT

Title of Invention:

CIRCULAR CAVITY LASER

RELATED APPLICATIONS:

Provisional Patent Appl. Nr. 60/236,446

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CIRCULAR CAVITY LASER

BACKGROUND OF THE INVENTION

Field of the Invention:

The present invention relates generally to the field of mode discrimination means in [disk and spherical] laser cavities, and in particular, mode discrimination in macroscopic cavities wherein a vast number of modes may otherwise be sustained.

Description of the Related Art:

The present invention relates generally to the field of lasers and optical resonator design, and in particular, to the fields of disk and spherical lasers. Also, the invention relates to [resonator] cavity structure designs that utilize multi-layer dielectric (MLD) thin film reflectors that provide a high degree of mode selection.

Laser [resonators] cavities of the disk and spherical geometries have become an increasingly intensive field of research; in particular, for such lasers that are fabricated on a miniature or microscopic scale. In the latter case, the predominant means of cavity reflection is through total internal reflection (TIR), which provides an extremely high cavity Q. Such reflective means normally manifest in "whispering modes," which propagate at angles below the critical angle for TIR. These microdisk and microsphere [resonators] lasers are very effective in cases involving evanescent coupling to an adjacent dielectric structure; however, they are known to contain a very large number of

competing high-order modes. In addition, the coupling of these whispering modes for useful work is difficult for applications not utilizing evanescent [propagation] coupling.

In recent years, theoretical studies have been performed on the development of derivation methods for cylindrical and spherical multilayer structures, which are aimed at providing an accurate description of the reflection coefficients and modal characteristics of these cavities. These studies address circular confinement structures with cavity dimensions on the order of the wavelengths studied. However, none of these studies are found to address the issues of applying [such] similar circular Bragg reflectors for larger cavities of the scale used for gas and larger solid state cavities. [These] Furthermore, these previous studies also entertain only the use of conventional MLD filters, with a large real refractive index difference, n_H-n_L = $\Delta n > 1$, for the layer pairs, and with an accordingly small number of layers required for high reflection.

The use of interference structures to enable high spectral resolving power in reflecting coatings has been described by Emmett (US Pat. No. 4,925,259), wherein a very large number of alternating dielectric layers possessing a very small difference in refractive indices is used for application in high power flashlamps. The described coatings are utilized primarily for providing a high damage threshold to the high irradiance experienced in the flashlamp enclosure, as well as for obtaining a well-resolved pump wavelength for use in the described flashlamp.

The control of transverse modes in semiconductor lasers, primarily VCSEL's, has been reported by several research groups in the last decade. These latter reports utilize a circular Bragg grating structure as a complement to the planar Bragg mirrors of a conventional, high Q semiconductor cavity. Such circular Bragg gratings do not form the initial resonant cavity, but rather, aid in controlling relatively low Q, transverse modes of an existing Fabry-Perot structure. In such cases, the resultant control of transverse propagation may allow lowered thresholds, or enhanced stability.

Earlier, large-scale, [resonator] <u>laser</u> designs of a circular geometry operated on very different principles than the microlasers, utilizing primarily gas laser mediums and metallic reflectors. In these earlier designs, optical power could be coupled for useful work at the center of the cavity, such as for isotope separation, or by using a conical reflector. Since, in these latter cases, laser modes that concentrated energy at the cavity's center were needed, some means for blocking the whispering-type modes was generally required. Such mode suppression was usually accomplished through radial stops; however, these stops only provided the most rudimentary mode control, in addition to hampering the efficient operation of the laser. Because of such issues, disk and spherical [resonators] <u>lasers</u> have not supplanted standard [resonators] <u>linear lasers</u> for any applications requiring substantial optical power or a high degree of mode selection.

SUMMARY OF THE INVENTION

A novel [optical resonator] laser apparatus has been developed for use in such applications as lasers and light amplifiers in general. The [resonator] laser developed comprises a [resonator] cavity mirror structure that provides a single surface of revolution. The cavity volume is defined by this surface of revolution, and contains the gain [media] medium. Unlike prior art disk and/or spherical lasers possessing circular cavities, the present invention does not rely on total internal reflection (TIR) or metallic reflectors to provide a high cavity Q-factor (and a broad range of high-order [propagation] modes). The [resonator] laser design of the present invention avoids use of these cavity confinement methods. In the optical resonator of the present invention, interference-based multilayer dielectric (MLD) reflectors are [developed that] constructed that can possess unusually narrow reflection peaks[. These narrow bandwidths provide] , corresponding to a degree of finesse (finesse designating interference-based resolving power) usually associated with MLD transmission filters of the Fabry-Perot type. The high-finesse MLD reflectors of the present invention conform to the surface of revolution of the [resonator] cavity mirror structure, allowing a high degree of angle-dependence for selective containment of [resonator] cavity modes. These filters are disposed in such a way as to allow [selection of] preferred low order modes (lower order modes being represented in the present disclosure as those corresponding to near normal incidence radiation) and suppression of parasitic modes while allowing a high cavity Q factor for the modes selected.

For a multi-layer dielectric (MLD) coating consisting of alternating layers, where all layers have an optical thickness equal to a quarter-wave of light at the wavelength of interest, the reflectance may be described according to:

$$R = \left[\frac{1 - (n_H/n_L)^{2p} (n_H^2/n_L)}{1 + (n_H/n_L)^{2p} (n_H^2/n_L)} \right]^2 \qquad (1)$$

wherein the index of refraction for the substrate is n_s, the two layer indices are n_H (high index) and n_L (low index), and the number of pairs of alternating layers is **p**. As is evidenced by equation (1), a higher reflectance may be achieved through the implementation of a greater difference in refractive index $\Delta n = | n_2 - n_1 |$. High reflectance is thus normally achieved by maintaining Δn at a relatively high value. However, as equation (1) suggests, high reflectance may also be achieved by depositing many layer pairs possessing a relatively low difference in their refractive indices. As the index difference decreases, many more pairs of alternating layers must be deposited to maintain reasonable reflectance. At the same time, this latter approach will result in a decrease in the bandwidth of light reflected by the resultant coating. The present invention utilizes MLD coatings which obtain high reflectance from an unusually low Δn; this is accomplished by maintaining a high degree of control over the properties of each layer through an unusually high number of iterations, **p,** of the layer pair. With well-controlled film characteristics, the reflectance of the resulting MLD coating is found to have a quite narrow bandwidth, typically in the order of nanometers.

A characteristic of the MLD coatings utilized in the present invention is the angle-dependence of the reflection peak. As the MLD coating is irradiated at increasingly oblique angles of incidence, the spectrally narrow reflection peak will be shifted toward increasingly shorter wavelengths. While the degree of this latter peak shift will depend on such issues as phase dispersion and the change in optical admittance with increasingly oblique incidence, the fractional shift in the peak transmittance will change generally with the phase thickness shift. As such, the fractional shift in peak transmittance will be slightly less than cos θ, where θ is the angle from normal incidence. As the angle of incidence, θ, increases, the magnitude of the reflectance peak [for the p polarization] will [decline] <u>generally decrease</u>, as well.

The aforementioned characteristics of these high-finesse MLD coatings are utilized in the preferred embodiments of the present invention. In accordance with the illustrated preferred embodiments, a novel laser [resonator has been developed] <u>cavity structure is disclosed herein</u> that effectively utilizes the sensitivity of the aforementioned coatings to angle-of-incidence when these same coatings are irradiated with quasi-monochromatic light. This is <u>normally</u> accomplished through the use of a [resonator] <u>cavity</u> mirror that conforms to a single surface of revolution. High confinement is achieved through <u>novel</u> use of the highly angle-dependent MLD reflectors [developed in the present invention]. Thus, instead of utilizing TIR or metal films, which both provide wide acceptance angles to high order [resonator] <u>cavity</u> modes, the present invention

utilizes external reflection and narrow acceptance angles to increase the stability of selected, lower order, [resonator] cavity modes.

Because the present invention does not rely on TIR or metallic films to provide high confinement for various laser modes, it is designed with a fundamentally different set of requirements for the refractive indices of its individual components. In contrast to the disk and spherical lasers of the prior art, the gain [media] medium – or, equivalently, the volume in which it resides – in lasers of the present invention should possess an effective refractive index, n_G, lower than that of the immediately surrounding medium. As such, the high index layers of the MLD of the present invention must have a refractive index, n_H, greater than that of the gain volume.

In one preferred embodiment, the present invention provides a laser [resonator] cavity structure that does not require a partially reflective mirror or external optics to efficiently couple laser light to a work piece or [medium] various process media. Instead, the laser [resonator developed] cavity structure disclosed herein allows [a photo-absorbing medium] photo-absorbing media to be introduced through the center of the cavity, so that energy not absorbed by the photo-absorbing [medium] media may contribute back to the energy stored inside the cavity. According to this aspect, the irradiation of [a photo-absorbing medium] photo-absorbing media may also be rendered highly uniform, and is well suited for media of substantially circular symmetry.

In another embodiment, the invention provides a unique configuration for coupling laser radiation from the edge of the spherical and disk lasers described, as the

mode selection provided allows efficient coupling of a low-divergence beam from the cavity edge. Other objects of the present invention follow.

One objective of the present invention is to provide a laser [resonator] <u>cavity</u> structure that allows [unusually] high thermal stability.

Another objective of the present invention is to provide a disk or spherical laser [resonator] <u>cavity structure</u> that discourages the establishment of whispering modes

Another object of the present invention is to provide a laser [resonator] <u>cavity structure</u> which allows mode selection through the use of all-dielectric reflectors of unusually high finesse.

Yet another object of the present invention is to increase the stability of conventional laser [resonators] <u>cavity structures</u> through the suppression of walk-off modes.

Another object of the present invention is to provide a laser [resonator] <u>cavity structure</u> that allows a low threshold to lasing.

Another object of the present invention is to provide a means for irradiating a photo-absorbing medium from a continuous 360-degree periphery.

Another object of the present invention is to provide a laser [resonator] cavity structure that allows efficient and reliable mechanical design.

BRIEF DESCRIPTION OF DRAWINGS

FIG. 1 is a delimited cross-sectional view of a thin film design for a MLD used in the preferred embodiment.

FIG. 2 is a reflectance curve for an MLD coating fabricated in accordance with the embodiments set forth in FIG. 1., showing normal incidence and tilted reflectance in the region of 300nm to 400nm.

FIG. 3 is a sectional top view of the invention in its first preferred embodiment.

FIG. 4 is a sectional side view of the invention constructed as a spherical [resonator] cavity laser.

FIG. 5 is a sectional side view of the invention constructed as a cylindrical [resonator] cavity laser.

FIG. 6 is a sectional top view of the invention in one of its embodiments, showing laser emission coupled from the edge of the cavity.

FIG. 7 is a sectional top view of the invention in another of its embodiments, wherein the cavity is pumped by an external light source.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

The following description and **FIGS. 1** through **7** of the drawings depict various embodiments of the present invention. The embodiments set forth herein are provided to convey the scope of the invention to those skilled in the art. While the invention will be described in conjunction with the preferred embodiments, various alternative embodiments to the structures and methods illustrated herein may be employed without departing from the principles of the invention described herein. Like numerals are used for like and corresponding parts of the various drawings.

In **FIG. 1** is a repeated scheme for the build-up of a high-reflectance MLD. The MLD contains **p** quarter-wave pairs, each consisting of a low index layer **(14)** and a high index layer **(15)**. The substrate **(1)** provides the surface of revolution onto which the MLD is deposited, thus forming the [resonator] <u>gas cavity laser</u> referred to in **FIGS. 3-7**. Each pair of quarter-wave layers **(14)** and **(15)** share a small refractive index difference, Δn, which is typically less than 0.2. The number of quarter-wave pairs, **p**, will typically be greater than 50 to maintain high reflectance. The quarter-wave pairs may be deposited

sequentially to achieve MLD's containing hundreds of layers. Materials used will depend upon the spectral region desired for lasing action. In many cases the small difference in real refractive index, Δn, may be achieved by making substitutions into the matrix of a parent material.

For instance, ZrO_2 may be deposited as the parent material by ion beam sputtering, thereby forming one of the quarter-wave layers. Subsequently, the second layer material may then be formed using the same process, while co-sputtering a second material, such as TiO_2, from a separate target in the same process chamber, resulting in the second layer being a mixture of the two oxides. As a result, the refractive index of the second layer may be controllably rendered slightly higher than that of the first layer; this, through the well-controlled addition of TiO_2 to a ZrO_2 matrix. The MLD, as shown in **FIG. 1**, may also be constructed with additional thin film structures incorporated for performing additional functions, such as anti-reflection [coatings,] coatings or secondary reflectors, and so forth. However, to achieve the finesse required in the present invention, the MLD design chosen for the [resonator] cavity mirror must incorporate a high number of quarter-wave pair iterations, accompanied by an unusually small index difference, Δn.

In **FIG. 2** [is a reflectance curve] are reflectance curves, in wavelength λ vs. % reflectance, for an MLD reflector fabricated according to the design set forth in **FIG. 1**, for light incident approximately normal to the substrate. The reflectance peak of the MLD reflector at normal incidence, as given by the solid line **(2)**, [demonstrates] is an

example of the narrow full-width-half-max (FWHM) [achievable] achieved with low Δn. The reflectance [curve] peaks of **FIG. 2** is [derived] obtained from [an] a MLD reflector containing ninety pairs (**p**=90) of the quarter-wave layers, with the index [split] difference of the pair, $\Delta n=0.04$. A topmost high-index layer **(19)** would typically be deposited to give maximum reflectance, resulting in an odd number of layers (in this case, 181 layers). The dashed [curve] line **(3)** in **FIG. 2** is the reflectance [curve] peak for the same MLD reflector when irradiated with light at an angle of 15° from normal incidence. The spectral shift [in the reflectance peak] between the two reflectance peaks of FIG. 2 is found to be approximately $\lambda_0 - \lambda_1 = \Delta\lambda = 5$ nm, while the magnitude of p-polarization peak reflectance is also found to drop from 95% to 94%. The magnitude of the peak reflectance may be increased through an increase in **p**; and, as peak reflectance increases, the latter 1% percent drop becomes an increasingly decisive factor in determining cavity Q, and mode selection, within the [resonator] laser cavity. A more narrow, or broad, FWHM **(16)** may be obtained by varying Δn according to the previously described relationships. In addition to the narrow FWHM, another useful characteristic of this MLD design, when incorporated in the present invention, is the pointed shape of the peak, as this pointed shape allows a more narrowly defined peak reflectance. The utility of these characteristics will become apparent when discussed in conjunction with the embodiments of **FIGS. 3-7.**

In **FIG. 3**, the present invention is shown in its first preferred embodiment. The substrate **(1)** provides the structure by which the surface of revolution, with axis of circular symmetry **(9)**, is defined. In the embodiments of **FIGS. 3-7**, this surface of

revolution will be identical to the interface between the substrate **(1)** and the MLD reflector **(5)**. The MLD reflector **(5)**, as described in **FIGS. 1-2**, conforms to this surface of revolution and modifies its reflective characteristics. The gain [media] medium for the laser is contained within the cavity [volume] interior **(4)**, formed by the substrate and integral MLD reflector. As such, if a fluorescent event occurs within the gain [media] medium, its confinement within the cavity is very much altered through the incorporation of the previously set forth MLD. The MLD limits the bandwidth of the laser emission, first through the interference filtering of the normal incidence emission, as practiced in the prior art. However the circular geometry of the present invention, combined with the [extreme] high angle-dependence of the MLD reflector, as described in **FIGS. 1-2**, requires that emission from the fluorescent event also propagate within a narrowly defined solid angle, if it is to be reflected back into the cavity [volume] interior **(4)**. Propagation which occurs outside this solid angle, such as indicated by solid line **(6)**, will be allowed to transmit outside of the cavity [volume] interior **(4)**, thereby avoiding the establishment of laser modes for such off-angle propagation. In the geometries described, these highly angle-dependent MLD reflectors thereby become a means of mode selection. The zig-zag line **(7)** which depicts the direction of mode propagation is only for demonstration, but indicates that the concentration of allowed modes is at or near normal incidence. The precise angle of the dominant mode will be determined by such design considerations as the [precise angle of incidence desired] preferred angle-of-incidence, the fluorescence spectra of the gain [media] medium, the type of coupling desired, etc.

In the [optical resonator] laser cavity structure of the present invention, confinement of the laser modes to paths that are at or near to normal incidence allows several unique coupling configurations. One such configuration is shown in **FIG. 3**, wherein laser radiation is coupled from the laser[, not through partially reflective mirrors, but] by introducing the media to be processed into the center of the laser cavity. This may be accomplished through implementation of a tube **(8)**, which separates the gain [media] medium from the process media passing through the tube interior, thereby providing a process volume within the cavity. The latter embodiment will be particularly effective in the processing of media that possess low absorption cross-sections, such as gases and vapors. Alternatively, the [volume] central coupling structure designated by the tube **(8)** may instead contain a cone-shaped optical element for extraction of laser light from the center of the cavity as has been described in numerous papers and patents of the prior art.

The cross-sectional figure of the [resonator] cavity mirror may be designed variously, dependent upon the type of gain [media] medium and lasing action required. In **FIG. 4**, the surface of revolution possesses a cross-sectional figure with a radius of curvature equivalent to that of the surface of revolution as viewed from the top in **FIG. 3**, thereby rendering it a spherical section. In this embodiment, laser emission is confined to propagate through a small volume (17) located at the center of the spherical mirror, intersected by the axis of circular symmetry **(9)**, thereby allowing an unusually high power density within this small volume.

Another embodiment of the present invention is presented in **FIG. 5**, in which the cross-sectional figure of the surface of revolution– again, identical to the MLD/substrate interface – is straight, thereby rendering the surface of revolution a cylinder. The cylindrical shape of the [resonator] laser cavity structure in the latter embodiment serves to demonstrate an added utility that is realized with the incorporation of the described MLD's. Unlike the [resonator] cavity geometries of the prior art, linear and other, which use relatively low-finesse reflectors, the present invention allows the stability associated with a particular cavity mirror selection to be increased. Whereas flat (or cylindrical) cavity mirrors will typically support parasitic "walk-off" modes which can decrease the overall Q-factor of the laser cavity, these same modes, such as exemplified by propagation direction **(6)** in **FIG. 5**, will be discouraged due to the low reflectivity of the cavity mirrors at these angles.

In an alternative embodiment of the present invention, laser radiation may also be coupled out of the laser cavity through the edge of the cavity, as in **FIG. 6**. This latter coupling may be accomplished by selectively removing or preventing the MLD deposition – through etching, masking, etc. – so as to provide an effective aperture **(10)** through which radiation may transmit. Benefits of the invention, as set forth in the embodiments of **FIG. 6**, include the ability to combine a high degree of mode selection with an unusually high cavity Q (and commensurately low threshold). [As such, the divergence of the emitted beam may be more easily controlled than with disk and spherical lasers of the prior art.]

In **FIG. 7** is another embodiment of the present invention that allows for edge pumping of the circular cavity. [While the] <u>The</u> laser cavities described in the present invention may comprise gas, solid, or liquid gain media, and may be pumped by any of the compatible methods described in the art<u>, such as by a discharge. Also,</u> the present invention allows for a unique method of optical pumping. Because of the reflectance and, inversely, the transmission characteristics of the high-finesse MLD's [developed for] <u>of</u> the present invention, lasers of the present invention may easily be pumped with laser radiation which corresponds to the peak absorption region of the gain medium's absorption spectrum. It is possible in the present invention to efficiently couple in the pump radiation through the [resonator] <u>cavity</u> mirror and MLD. In this manner, diode lasers could be positioned around the periphery of the [resonator] <u>cavity</u> mirror.

It should be noted that, in embodiments of the present invention where the laser cavity is fabricated with a disk-like aspect, thermal stability is typically more easily obtained than in other laser cavities. This latter advantage is due to the ability to effectively heat-sink the cavity through its planar sides – as indicated by dashed lines **(18)** in **FIGS. 4-5** – as these surfaces need not be transparent. In fact, these surfaces can possess any of a number of reflecting, absorbing, or scattering characteristics, depending on the application. The ability to heat-sink these cavities can be particularly important in the case that the gain [media] <u>medium</u> is solid state. Heat-sinking <u>, in such a case,</u> may also be performed effectively through the [resonator] <u>cavity</u> mirror, as long as the outer layers of the [resonator] <u>cavity</u> mirror are specified so as to prevent <u>any possible</u> TIR of [the] <u>unwanted</u> laser wavelengths. If the [resonator] <u>laser cavity structure</u> of the present

invention is to be operated in an ambient medium which possesses a refractive index, n_A, substantially lower than n_G, then an absorbing and/or scattering layer is preferably utilized externally to the MLD. This latter use of an absorbing and/or scattering layer serves to prevent specular reflection of unwanted cavity emissions back through the MLD to re-enter the gain volume. Such measures could be implemented in the case that the gain [media] medium is solid state.

It is not intended that the MLD reflector be restricted to the embodiments of **FIG.1**, as the latter embodiments are presented primarily for the purpose of teaching the invention. The MLD implemented in a particular embodiment will depend on its particular requirements. The MLD may comprise organic or inorganic materials, or a combination of both. The design of the MLD reflector may vary considerably, as well. For instance, certain layer pairs within the MLD may possess a much higher Δn without appreciably increasing the FWHM of FIG. 2. The thin film materials utilized may possess amorphous or crystalline microstructures; and as such, may be optically isotropic, uniaxial or biaxial, depending upon the precise transmission characteristics of the MLD reflector. The MLD reflector may, in some applications, be designed for peak reflectance at a relatively large angle of incidence. Various other functions may also be incorporated into the MLD design, such as an anti-reflection coating, or the transmission of a particular fluorescence peak.

It should also be noted that the embodiments of **FIGS. 3-4** do not require that the described spherical [resonator] cavity laser be restricted to any particular major spherical

section. In fact, the [resonator] cavity structure sectional view of **FIG. 4** may as easily describe operation of a [resonator] cavity structure that is not truncated at all, so that the [resonator] cavity is a complete sphere. Also, the MLD described herein may, in many circumstances, be deposited on the external surface of the substrate, therein defining the required surface of revolution. In these latter circumstances, the substrate would reside within the [resonator volume] cavity interior, and hence would need to be quite transparent to the desired wavelengths. Such a case might be when the required surface of revolution is the external surface of a sphere, which is composed of a laser glass or crystalline material.

The present invention is seen to have potential applications in several areas. One such application would be in the treatment of optical fibers or optical fiber preforms, where the fiber or preform could be passed through the center of a laser cavity similar to that described in **FIG. 3**. Another potential application could arise in the general field of vapor deposition, where various vapors or gases might be ionized, heated, or otherwise altered by passing through the process volume of **FIG. 3**. [Yet another potential application for the present invention is in the area of micro-optics.] [For example, microspheres of SiO_2 could be coated with MLD's in accordance with the embodiments of the present invention.][These same microspheres could be fabricated with fluorescing components incorporated into the SiO_2 matrix, therein providing a laser structure that might be pumped by various means.][Alternatively, the gain material might be a semiconductor, as well; as such, the MLD reflector would allow photoluminescence, or be designed of semiconductor materials that allow cathode luminescence or charge injection of the gain medium.]

The preceding description provides an [optical resonator] laser cavity structure that may be operated as a laser, optical amplifier, or other, optically resonating, device. Although the present invention has been described in detail with reference to the embodiments shown in the drawings, it is not intended that the invention be restricted to such embodiments. It will be apparent to one practiced in the art that various departures from the foregoing description and drawings may be made without departure from the scope or spirit of the invention.

What is claimed is:

1. A structure for providing optically resonant modes, comprising:

   a.) a cavity structure providing a surface of revolution;

   b.) a multilayer dielectric reflector deposited on the surface of revolution, the reflector defining an optically resonant cavity with resonant modes, the reflector substantially delimiting propagation within the cavity to preferred resonant modes;

   c.) an optical gain medium within the optical cavity, the medium disposed for emitting optical radiation into the preferred modes.

2. The structure of Claim 1, wherein the medium is pumped by a discharge.

3. The structure of Claim 1, wherein additional layers are deposited for additional functions.

4. The structure of Claim 1, wherein the multilayer dielectric reflector contains more than 60 layer pairs, the pairs having a refractive index difference, $n_H - n_L < 0.2$.

5. The structure of Claim 1, wherein a material with an optical absorption cut-off limits unwanted propagation in the structure.

6. The structure of Claim 1, wherein the structure also defines a central process space in a central region of the cavity.

7. The structure of Claim 1, wherein a substantially conical reflector is used to reflect the radiation.

8. The structure of Claim 1, wherein the radiation is used for materials processing.

9. The structure of Claim 1, wherein the radiation is used for the treatment of optical fiber.

10. The structure of Claim 1, wherein the radiation is used for the treatment of optical fiber preforms.

11. The structure of Claim 1, wherein the radiation is used for the treatment of semiconductor processing gases.

12. The structure of Claim 1, wherein the gain medium is a gas.

13. The structure of Claim 1, wherein the gain medium is solid state.

14. The structure of Claim 1, wherein the surface of revolution is discontinuous.

15. The structure of Claim 1, wherein the reflector is discontinuous.

16. The structure of Claim 1, wherein the gain medium provides a narrow fluorescence spectrum.

17. The structure of Claim 1, wherein radiation is coupled through the surface of revolution.

18. A structure for providing optically resonant modes, comprising:

a.) a cavity structure providing a spherical surface of revolution;

b.) a multilayer dielectric reflector deposited on the surface, the reflector defining an optically resonant cavity with resonant modes, the reflector having an angle-dependence, so that mode propagation within the cavity is substantially limited to preferred resonant modes; and,

c.) a gain medium within the cavity, the medium disposed for emitting optical radiation into the preferred modes.

19. The structure of Claim 18, wherein the cavity comprises a solid, the solid transmitting a desired optical spectrum.

20. The structure of Claim 18, wherein the gain medium is a gas.

21. A structure providing optically resonant modes, comprising:

a.) a cavity structure providing opposing optically reflecting surfaces, the opposing surfaces defining a cavity;

b.) a multilayer dielectric reflector deposited on at least one opposing surface, the reflector composed of at least one hundred-twenty (120) alternating layers of high index n_H and low index n_L, wherein n_H and n_L are real refractive indices, wherein $n_H - n_L < 0.1$;

c.) an optical gain medium substantially within the optical cavity, the medium disposed for emitting radiation, a solid angle of propagation for the radiation being delimited by the reflector.

ABSTRACT

A novel laser apparatus is disclosed which pertains to laser resonator geometries possessing circular symmetry, such as in the case of disk or spherical lasers. The disclosed invention utilizes multi-layer dielectric (MLD) thin film reflectors of [unusually high-finesse] many layer pairs of very small refractive index difference, the MLD deposited on a surface of revolution, thereby forming an optical cavity. These [filters] dielectric reflectors are disposed in such a way as to allow selection of preferred low order modes and suppression of parasitic modes while allowing [an extremely] a high cavity Q factor for [the modes selected] preferred modes. The invention disclosed, in its preferred embodiments, is seen as particularly useful in applications requiring high efficiency in the production and coupling of coherent radiation. [The invention is also well suited for achieving mode selection and narrow line-widths.] This is accomplished in a cavity design that is relatively compact and economical.

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NEW CLAIM

23. A circular laser for sustaining lasing cavity modes with an optical radiation of wavelength, λ, comprising:

a.) cavity structure means providing a surface of revolution, the surface thereby having a circular aspect;

b.) a reflective coating deposited on the surface of revolution, the coating providing a circular optical cavity, the optical cavity having a cavity interior with an interior index of refraction, the coating including at least one hundred thin film dielectric layers, the layers having alternating refractive indices, the alternating refractive indices at least as great as the interior index, the alternating refractive indices differing by less than 0.2, the coating providing greatest reflectance to the radiation at an angle-of-incidence, so that the coating is substantially reflecting to the radiation only at approximately the angle-of-incidence, such that the radiation only contributes to the modes when the radiation is propagating at approximately the angle-of-incidence;

c.) an optical gain medium in the cavity interior, the medium disposed for emitting the radiation into the modes; and,

d.) optical pumping means for excitation of the gain medium.

~~I don't see this method ... selection ...~~ not in fact